THE NEXT GENERATION SPACE TELESCOPE (NGST) - SCIENCE AND TECHNOLOGY

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Abstract

The scientific requirements and the implications for the instruments and telescope design for the Next Generation Space Telescope are described. One candidate concept is a deployable 8 meter diameter telescope optimized for the near infrared region (1-5 μm), but with instruments capable of observing from the visible all the way to 30 μm. The observatory is radiatively cooled to about 30 K and could be launched on an Atlas II-AS to the Lagrange Point L2.

INTRODUCTION

The Next Generation Space Telescope is conceived as the successor to the immensely successful Hubble Space Telescope (HST). The HST examines the most distant reaches of the universe yet seen, reaching billions of light years to look back to a time when conditions were very different. It has shown us tantalizing hints of the growth and evolution of galaxies, and may even have located some tiny objects at a redshift of 2.39 that would eventually merge to form galaxies. The expansion of the universe is conveniently measured by the redshift z, where 1+z is the ratio of the wavelength of light we measure now, to the wavelength it had when it was emitted. The same 1+z is also the ratio of the size of the universe now to the size of the universe at the time that light from a particular object was emitted toward us. The cosmic redshift effect means that most of the light of the most distant galaxies and their precursors is detectable only with infrared instruments. Many of the objects seen in the Hubble deep field, a region that was examined with a MANY day time exposure, are very red and presumably very highly redshifted.

Even before these recent results, AURA's HST & Beyond Committee (Dressler et al. 1996) recognized the enormous scientific capabilities of a large-aperture, infrared-optimized space telescope and recommended strongly that such a mission be developed to follow the HST and SIRTF programs. The Committee, chaired by Alan Dressler, recommended a passively cooled telescope be built to carry out the core mission of studying the early formation of stars and galaxies at high redshift. A diameter of at least 4m, depending on wavelength, would be needed to provide resolution comparable to HST (corresponding to scales lengths of about 1 kpc at high redshift) and the sensitivity to detect the compact, essentially unresolved star forming regions in early galaxies ($3 < z < 10$). The HST & Beyond report also listed a wide range of additional scientific research which would be enabled by such a facility in both the optical and the thermal infrared.

The practical limitations of ground based astronomy may soon be reached with the current generation of 8 and 10 meter telescopes when they are fitted with active optics to compensate for atmospheric turbulence. Matt Mountain of the Gemini project of the National Optical Astronomical Observatory has argued that the next generation ground observatory that would be required to take spectra of all the objects seen in the Hubble deep field would need the collecting area of a 50 meter telescope and would cost of order $1 billion. Atmospheric turbulence can only be partially overcome by active optics, which can not make sharp images over wide fields, and especially for large telescopes can not achieve high Strehl ratios (i.e. most of the light of a star is not in the high resolution core of the image). At wavelengths longer than about 2 μm, telescope and atmospheric thermal emission are of order 1 million times brighter than the zodiacal background that limits observations in space. Worse yet, many wavelengths are blocked entirely by atmospheric absorption lines.

With support from NASA Headquarters, the Goddard Space Flight Center (GSFC) and the Space Telescope Science Institute (STScI) began a feasibility study of a large passively cooled telescope, dubbed “NGST” after the NGST Workshop (STScI 1989). MSFC (Marshall Space Flight Center), JPL (Jet Propulsion Laboratory), and the Ames and Langley Research Centers and many engineering firms have participated in the study. To gather the best ideas that academia and industry have to offer, NASA has also funded two independent studies by industrial and academic consortia. The Lockheed-Martin team is led by D. Tenerelli and the TRW team by C. Lillie. The results from all three studies were presented in August and September, and all three of the September viewgraph presentations are available from our Web site at http://saturn1.hst.nasa.gov/ngst/.

The goal of the study was to find a way that the NGST can be built for $500 M (FY 96 funds) with a life cycle cost of $900 M, not including data analysis or technology development. This is very small compared to the HST life cycle cost, of order $6B. The plan is designed for a launch around 2005. All three studies concluded that the cost and schedule are feasible, given a proper technology development program beginning now.

STRAWMAN SCIENCE PROGRAM

Clearly, astronomy will always benefit from bigger and better telescopes; and a compromise must be found between technical and financial feasibility and scientific capabilities. In order to better understand the interplay of the various observatory parameters, we established a volunteer Science Working Group (SWG) and an officially chartered Science Oversight Committee (SOC), chaired by R. Kennicutt. The SOC includes several representatives of the European community. The SWG developed a strawman observing program mostly based on the prime targets identified in the "HST & Beyond" report. This observing program was defined iteratively by testing scientific requirements against realistic capabilities and mission lifetime. This process was facilitated by formulating each type of target requirement in a computer program allowing for the testing of different instrumental parameters.

Although the program is heavily weighted toward cosmological problems, we intend to have a balanced share between the various scientific research themes. About 51% of the proposed observing program is dedicated to a Core program directly linked to NASA's Origins Program and implementing the various aspects of the Origins of Galaxies study as outlined in the "HST and Beyond" report. This Core program is the minimum program that a mission of this type should try to achieve. The rest is devoted to science projects not related to the Origins of Galaxies studies but infeasible with other kinds of instruments. Although the selection of the scientific program elements is somewhat subjective and dependent upon current scientific interests, it is broad enough to be generically representative.

A brief description of each of the research goals and of the corresponding observational parameters is given below.

- Supernovae study (Core). The interest is twofold: one can use the SN as standard candles to improve our knowledge of the geometry of the Universe (q_0 and λ), and also use them to study the material universe before the birth of galaxies. These goals are achieved by identifying about 100 SNe at redshift greater than 2 (i.e. down to K_{AB} 31), following them for two "rest frame" weeks before and two after maximum. The study includes low resolution spectroscopy. Additional SNe will be identified while monitoring the 100 main objects.

- Deep Fields (Core). One deep field (down to K_{AB} magnitude 32) and 100 less deep (K_{AB} 30) flanking fields will be observed in several broad band filters. Several classes of objects will be identified in these fields. Galaxies at redshift greater than 2 will be studied spectroscopically at low and high resolution to derive their redshift, their spectral energy distribution, and their internal kinematics to study the early evolution of galaxies and of their dark matter content.

- Universe at redshifts $z > 2$ (Core). This includes followup studies of objects identified in the Deep Fields and searches for relatively bright but rare objects. In particular, primeval spheroids, birth and evolution of disks, the origin of heavy elements, birth and evolution of AGN are all included in this category.

- Cosmic Distances. Includes studies based on gravitational lensing and gravitational time delays.

- Stellar populations in the nearby universe. For both local group and Virgo Cluster galaxies color-magnitude diagrams will be obtained down to the horizontal branch luminosity both in the optical and in the near infrared.

- Individual object classes. A variety of studies in both imaging and spectroscopy that can take advantage of the NGST performance. Collectively these projects make up 17% of the program.

- Kuiper Belt object searches. The searches will be carried out down to magnitude AB 30 in the optical

THE OPTICAL TELESCOPE ASSEMBLY AND SPACECRAFT CONCEPT

Current launchers cannot accommodate payloads with diameter larger than 4 meters. Since an 8 meter aperture was set as a goal for the study, the primary mirror had to be deployable in the manner of those developed for ballistic missile defense requirements. The paper by Bilbro et al. (1996) illustrates possible concepts and describes the technological developments needed for them. An alternate concept suggested by Lockheed-Martin would require a larger payload fairing and a nondeployable mirror. Briefly, whether deployed or monolithic, the primary mirror is an extremely thin face sheet (~2mm thick), which could be of glass, silicon carbide, beryllium, nickel, aluminum, or a composite material. This reflecting surface is supported by an integral structure or by a separate one, which need not be the same material. In all cases adjustment is required after launch. This can be done by adjusters distributed across the mirror, or with a deformable mirror located at an image of it.

Pointing control for the NGST need not be done the same way as in the HST, which was a rigid structure pointed as a unit to a precision of a small fraction of an arcsecond. The NGST could use a fast steering mirror in the instrument area to track a 19th magnitude star. There is no requirement for precise astrometry with NGST.

There are several deep space orbit choices, all of which have the advantage of avoiding thermal and straylight problems from the low Earth orbit of the HST. An orbit around the Sun-Earth Lagrange point L2, located 1.5 x 10^6 km from the Earth on the Sun-Earth line, provides all these advantages. With all the heat sources on side, a single sun shield can protect the telescope and allow strong radiative cooling. Analysis shows that a temperature of 30 K is readily achieved with enough layers in the shield and a minimum of heat dissipation in and near the mirror. If an orbit as far as 3 AU from the Sun could be achieved, the zodiacal emission which provides the unavoidable photon noise floor would be reduced by about two orders of magnitude, but unless detectors are improved by a similar factor the full advantage would not be obtained.

THE SCIENCE INSTRUMENT MODULE

There are many choices for implementing the cameras and spectrometers required by the scientific goals. The critical choice is the detector set. The primary wavelength range from 0.5 to 5 μm can be covered by InSb photovoltaic arrays, which operate well at 30 K. They are already very good, but larger 8192x8192 formats (achievable by mosaicing) and lower dark currents and readout noises are desired. For shorter wavelength coverage, CCD's or direct readout silicon arrays made like the InSb arrays are of interest, but the CCD's need a higher temperature, of order 120 K. For wavelengths from 1 to 10 μm, and possibly longer, HgCdTe detectors are candidates. They are already in use for the NICMOS on HST for the 1-2 μm region. For wavelengths from 10 to 26 μm, Si:As photoconductive Blocked Impurity Band (BIB) detector arrays are the only reasonable choice, but they require cooling to around 6 K, and they need improved sensitivity and larger formats (1024x1024) as well.

The near infrared camera and detectors are operated at the nominal 30 K, at which temperature the Science Instrument Module can be passively cooled. At this temperature the thermal emission of the optics and the detector dark current are negligible. This is not the case in the thermal infrared and critical elements of the TIR camera and spectrometer must be cooled actively, the filters and cold stop down to about 15 K and the detector down to at least 8 K. The temperature requirement would be eased if HgCdTe detectors with longer wavelength coverage (out to 10 μm) could be developed with low enough dark current, and if the scientific requirement for longer wavelength coverage were removed. Using a cryogenic Dewar was rejected in these studies because of the volume and weight. Cooling for 6 K is achievable with reverse Brayton turbo coolers with < 60 W input, < 10 kg mass, and negligible vibration (Swift 1995 and McCormick 1995), or with Joule-Thompson expansion from hydrogen and helium sorption pump coolers being developed at JPL by L. Wade et al., but both need further development.

Optically, the cameras and spectrometers are straightforward, except for one important innovation. Medium resolution (R = 1000) spectroscopy of a large number of faint objects is a central theme of the scientific requirements. Most of the faint objects observed by HST are already too faint to observe spectroscopically with much larger telescopes on the ground. For survey work, collecting large area images or large numbers of spectra simultaneously is as important as having a large telescope. Hence, one of the NGST instruments must be a multiobject spectrograph capable of obtaining simultaneously dozens to hundreds of individual spectra over a wide angular field. There are and near infrared and AB 25 in the thermal infrared. This would allow for a statistically meaningful study of their properties as well as of the distribution in space.

Having defined a strawman science program, it is a simple matter to study the role of the main instrumental parameters on the scientific capability of the mission using the completion rate of the program over a given mission lifetime as a figure of merit. In particular, the influence of the telescope diameter, instrument field of view, optics temperature, optics throughput, parallel use of instruments (several instruments observing the same field either simultaneously or successively if they do not share the same field of view), detector readout and dark current noise, can readily be quantified.

The main conclusions which can be drawn from these trade-off studies are as follows:

- The science program is driven by sensitivity in natural background-limited conditions, not by angular resolution. As a result, the aperture configuration should be as compact as possible, with a full circular aperture preferred. Multiple, separated apertures and interferometric systems would be far less efficient.

- A 6 meter effective aperture telescope with the proposed set of instruments would be adequate to complete all core programs and most of the complementary program in a 5 year mission.

- To some extent, telescope diameter and field of view can be traded against each other. This is because the scientific program is dominated by surveys in background limited mode, not by individual targets or high resolution programs. Since instruments are typically less expensive than telescopes, this indicates that instruments should be built with as large a field of view possible, i.e. within the limit allowed by optical aberrations and packaging.

- The optics temperature must be below 60 K so that the telescope emission will be negligible for the core program (up to 5 μm) compared to the natural zodiacal background, and less than 35 K to enable the thermal infrared science program.

- The detector dark currents should be improved by a factor of 5 over the current state of the art (~0.1 electron/s per pixel) so that detectors do not limit sensitivity.

- The figure of merit for the observatory has many factors, but a rough estimator is proportional to $D^4 t N_{pix} E / NEP^2$ where D is the telescope diameter, t is the observing time, N_{pix} is the number of resolved pixels, E is the efficiency, and NEP^2 is the square of the detector noise equivalent power. Where zodiacal light dominates the detector noise, the NEP^2 is proportional to Z, the zodiacal light brightness. This figure of merit applies to point source photometry of faint objects, and is not strictly applicable to other measurements.

The desired characteristics of the observatory resulting from the original HST & Beyond recommendations and these science program analyses are summarized in Table 1.

Table 1. Desired Scientific Requirements

Item	**Required Performance**
Angular resolution	< 60 milliarcsec at 2 μm
Limiting magnitude	up to 32 AB
Spectral range	1 to 5 μm (0.6 to 26 μm goal)
Spectral resolution	up to 1000
Field of view (simultaneous imaging)	4 x 4 arcminutes
Instrumental background	< zodiacal light at 1-5 μm
Optics temperature	< 60 K (30 K goal)
Detector dark current	< 0.02 electrons/sec/pixel
Instantaneous sky coverage	> 20% available
Mission sky coverage	100% available
Mission lifetime (yr)	10

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several concepts for such a spectrograph, including the use of microlens arrays to break a compact portion of the focal plane into hundreds of separated apertures and spectra. The Digital Micromirror Array, a remarkable innovation by Texas Instruments (Mignardi et al.) offers a very nearly ideal possible solution. The array has been developed for projection television as an addressable light switch. Each element in the array is a 15 μm square mirror, which can be tilted +/- 20° from the rest position. The array would be used as a switchable slit at the entrance to a grating or grism spectrometer. Properly utilized, such a device could enable simultaneous spectroscopy of hundreds of objects over a wide field of view. However, development would be required for optimum use. This would include cryogenic operation, and for longer wavelengths an increase in the mirror element size. We would like an array size of at least 1800x1800. This would allow an angular resolution of 0.1 arcsec over a 3 x 3 arcminute field.

The Micromirror Array also allows autonomous operation. It should be possible to take an image of an interesting area, which would be analyzed onboard to recognize the locations of objects meeting certain selection criteria for spectroscopy. The Micromirror Array would then be commanded to send light from just those objects on to the spectrograph.

It is clearly too soon to specify the exact instrument complex for the NGST, which will not fly for about 10 years. It must be the successor for instruments (like the HST NICMOS, the Near Infrared Camera and Multiobject Spectrometer) and telescopes like the SIRTF, SOFIA, and WIRE, none of which have been flown. We also expect great progress from the Keck, Gemini, VLT. and other ground-based observatories. However, one can anticipate possible additional instruments that might be proposed. For example, a coronagraph or a rotation shearing interferometer could be used to search for planets or brown dwarf stars near brighter objects. Longer wavelength instruments would also benefit from the large cooled aperture of NGST, provided that they could be accommodated with little cost impact.

SUMMARY AND CONCLUSIONS

A Next Generation Space Telescope meeting the goals of the HST and Beyond report is feasible with a reasonable extension of present technology. This means an aperture greater than 4 m with radiative cooling to reach the zodiacal background sensitivity limit from 1 to 5 μm wavelengths, and a goal of much wider wavelength range from 0.5 to 30 μm. The instruments should include wide field cameras and multiobject spectrometers. With a launch on an Atlas IIAS class expendable rocket to an orbit at the Lagrange Point L2, it would be much less massive than the Hubble Space Telescope, and much less expensive. The L2 orbit permits much simpler operations, without constant interruption by the Earth in the line of sight. It also permits simple and very effective radiative cooling, so that the telescope can easily reach below 60 K and the instrument chamber below 30 K. Three independent studies performed by a Government-led team and by TRW-led and Lockheed-Martin led teams all concur with this fundamental conclusion.

Acknowledgments

The Government-led part of the NGST feasibility study is the work of a large integrated product team composed of individuals from NASA centers, the Space Telescope Science Institute, the Johns Hopkins University, the University of Rochester, the University of Arizona, and several industrial companies including particularly Ball Aerospace Co., Left Hand Design, and Santa Barbara Research Center. The TRW and Lockheed-Martin studies also represent very large and creative collaborative efforts.

References

Bely, P.Y, Burrows, C.J., and Illingworth, G.D, eds. (1989) "The Next Generation Space Telescope (NGST)." Proc. workshop, Space Telescope Science Institute. Avail. Space Telescope Science Institute, Baltimore, MD.

Bilbro, J., Coulter, D., and Martin, G. L., (1997) "Technology Requirements and Plans for the Next Generation Space Telescope," in Proc. Space Technology and Applications International Forum CONF-970115, M.S. El-Genk, ed.

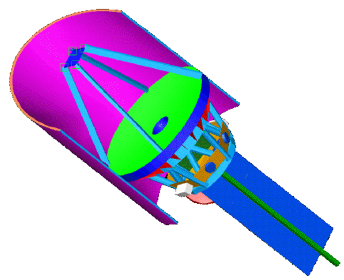
Dressler, A., et al. (1996), "HST and Beyond," Avail. Space Telescope Science Institute, Baltimore, MD. Electronically available via link from NGST home page, http://saturn1.hst.nasa.gov/ngst/.

McCormick, J. A., et al. (1995) "Miniaturization of Components for Low Capacity Reverse Brayton

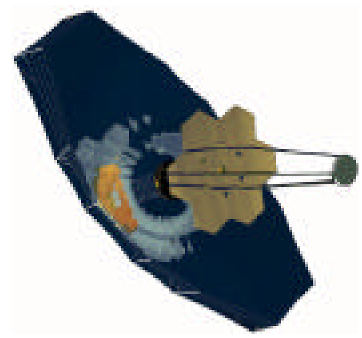
Cryocoolers". Cryocoolers 8. R. G. Ross, Jr. Ed., Plenum Press. 507-515

Swift, W.L., (1995) "Single-Stage Reverse Brayton Cryocooler: Performance of the Engineering Model". Cryocoolers 8. R. G. Ross, Jr. Ed., Plenum Press. 499-506

GSFC



Lockheed-Martin



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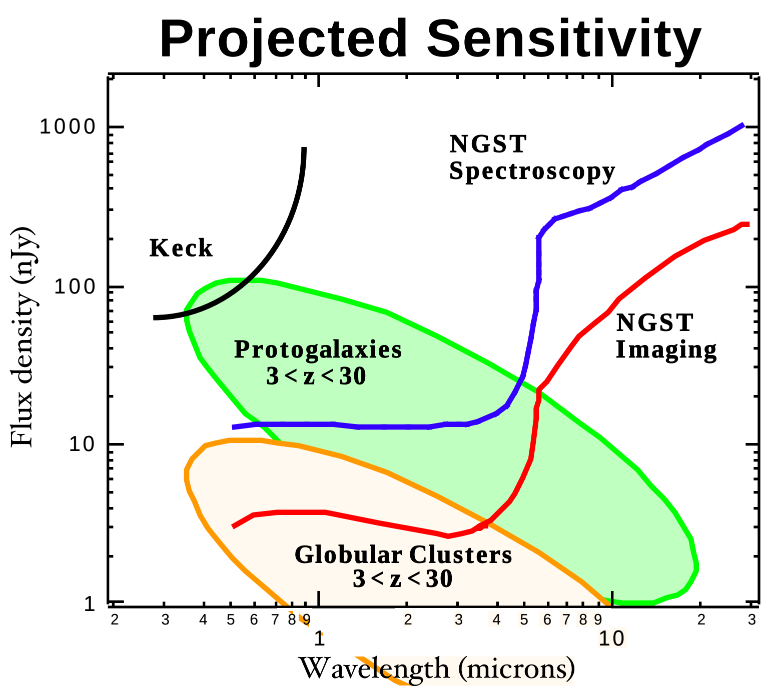

Sensitivity of an 8m diameter NGST compared with various astronomical phenomena in the early universe. The NGST curves, wide band imaging mode and low resolution spectroscopy R~100, are for a 10000 second exposure.